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TRANSIENT SAND TRANSPORT RATES AFTER WIND TUNNEL START-UP

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ABSTRACT

Wind tunnel experiments were conducted with a well mixed, flat sand bed, 5·7 m in length, to study the initial sand flux response at three different shear velocities. In some experiments, the bed was allowed to deplete without replenishment; in others, sand was fed 10·8 m upstream of the monitored cross-section. The results indicated that the transport rate increases rapidly during the first minute, and then adjusts slowly towards a steady rate. The time to reach such an equilibrium was observed to be on the order of 2–4 min in non-fed experiments and on the order of 8–9 min in fed experiments.

Many factors may affect such development and bring about non-stationarity in total sand transport rate. Among these factors are differences in the natural composition of the sand bed, changes in both the topographical features of the sand bed (ripples) and its surface texture, and any artificial features that influence the adjustment between the boundary layer profile and the sand load on the wind. A useful key to the influence of each factor is obtained by noting that each has a typical and distinct ‘time constant’. The nature and relative importance of each is discussed by reference to the reported wind tunnel experiments and to the behaviour of saltation cloud numerical models. © 1998 John Wiley & Sons, Ltd.

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KEY WORDS: wind tunnel; sand transport rate; saltation

INTRODUCTION

Numerical simulations by Anderson and Haff (1991) and McEwan and Willetts (1991) suggested that as the wind blows, the sand transport rate adjusts very quickly to flow changes. Their models indicate that the sand transport rate grows very rapidly during the first second until it reaches a peak value. It then decays slowly to achieve a steady state. Anderson and Haff (1991) found that the steady flux is achieved within 2 s while McEwan and Willetts (1991) found this achievement to be on the order of tens of seconds. However, these studies did not explore whether the transport rate peak and the attainment of equilibrium are affected by downwind distance from the leading edge of the sand bed or by change of surface sorting and relief.

Stimulated by Bagnold’s (1941) work, numerous data on the relation of aeolian sand transport rate and wind flow have been published during the last three decades. These experimental data were used mainly to derive expressions for the developed steady mass transport rate. However, Butterfield (1991) used wind tunnel data to study response times for stabilization of transport rate in steady-state saltation. Through his experiments, which were run for short periods of time, he aimed to understand the role of wind gustiness in sand transport. His results confirmed that saltation systems respond to flow changes within 1–2 s. Butterfield (1993) then presented new experimental data demonstrating aspects of the response of an aeolian saltation system to fluctuating wind velocity. These later experiments permitted verification of some aspects of the Anderson and Haff (1991) and McEwan and Willetts (1991) models.

To further investigate transient sand transport rates when wind is first introduced to a sand bed, a series of wind tunnel experiments was conducted at the Department of Engineering, University of Aberdeen, and is reported in the remainder of the paper. It was the strategy of this study to investigate the sand transport response to wind velocity in two different cases. In the first case, the sand bed was allowed to deplete without

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replenishment, and in the second case, depletion was prevented by sand being fed at approximately the equilibrium transport rate. The comparison between the cases is relevant to the design of wind tunnel procedures, which often introduce fed sand in order to develop uniform conditions in a shorter development length and, more generally, to the consideration of feed conditions that impose a sediment supply discontinuity.

In wind tunnel experiments, Bagnold (1941) found that the distance required to achieve equilibrium saltation in the absence of sand feed was between 4 and 7 m, and seemed to be independent of the shear velocity. White and Mounla (1991) determined experimentally that a minimum entrance length of at least five times the height of the tunnel is necessary to develop equilibrium saltation. Al-Sudairawi (1992) conducted several experiments, in the same wind tunnel as was used in this study, to determine the effect of the length of the sand bed on sand flux. He found that in the absence of sand feed, the sand flux increased over the sand bed for approximately 6 m before it reached equilibrium. He also showed that the length required to attain an equilibrium rate of sand transport decreases with increasing shear velocity. Shao and Raupach (1992) reported experimental results from a study of saltation in a wind tunnel with a working section 17 m long, 1·5 m wide and 0·9 m high. They found that the sand transport rate increases from zero at the upstream edge of the sand bed to a maximum value at around 7 m downwind, and that the minimum distance required for sand transport to reach equilibrium (about half the maximum value) is approximately 15 m, depending on wind speed. Any measurements of the sand transport rate at a downstream distance of roughly 7 m may therefore overestimate the sand flux value. This is also supported by the numerical experiments of Spies (1995).

EXPERIMENTAL SET-UP AND PROCEDURE

A 12-m long wind tunnel with cross-sectional dimensions of 0·5 m by 0·5 m was used to conduct the experiments. A schematic view of the wind tunnel is shown in Figure 1, and the wind tunnel is fully described by Rice (1990). A new sand feed system was built to carry out this study. The system, which was installed 41 cm downwind of the wind tunnel's entry, is shown schematically in Figure 2. The system is capable of supplying sand into the wind tunnel at a predetermined rate with an accuracy of about ±1·7 per cent at a preselected height above the bed.

To reduce the large erosional capability of wind flow at the upstream end of the wind tunnel and to ensure that a fully rough condition was achieved within a short distance, static roughness was created by means of cylinders 11 mm tall and 9 mm in diameter, evenly and uniformly spaced at a centre-to-centre distance of twice the cylinder's diameter. This roughness extended for a distance of 1·5 m downstream from the position of the sand feed tubes. According to Rasmussen and Mikkelsen (1988), an obstacle height of 11 mm gives approximately the same order of magnitude of roughness height ($z_0 \cong 5$ per cent of the obstacle height) as can be extrapolated from the wind profile during sand transport. We note that the saltation roughness height varies with the size distribution of sand grains, and therefore it is likely to vary from one set of experiments to another.

In these experiments, a series of measurements of the sand flux at three preselected shear velocities was performed on a 2 cm thick bed of sand having an average grain diameter of approximately 275 μm (Figure 3). The sand was well mixed and laid flat over a length of 5·7 m from the downwind edge of the artificial static roughness.

A vertical pitot static tube rack (each tube having an outer diameter of 2·1 mm and an inner diameter of 1·85 mm) measuring the dynamic and static pressure at three different heights, namely 7·5, 17·5 and 41·5 mm above the sand bed, was used to determine the shear velocity above the sand bed layer at a distance of 6·245 m downstream from the position of the sand feed tubes. The rack was designed in such a way as to be suitable for shear velocity measurements in the clean-air and sand-flow experiments when it was fixed at an appropriate height. The design was based on a suggestion of Spies *et al*. (1995) that the velocity profile slope in the lower, constant-stress region (i.e. when $30 < zu_*/\upsilon \leq 3000$) is suitable for the determination of shear velocity. The selected range of heights of measurement lies within the range of this lower portion of the wind profile during sand movement.

A sand trap, with inlet width 2 cm and height 20 cm, was used to record sand flux at 3·6 m downwind from the downstream end of the sand bed. On the 3·6 m length of uncovered, hard floor surface, no sand accumulated and therefore the sand transport rate as measured in the sand trap reflected the value of sand flux leaving the sand

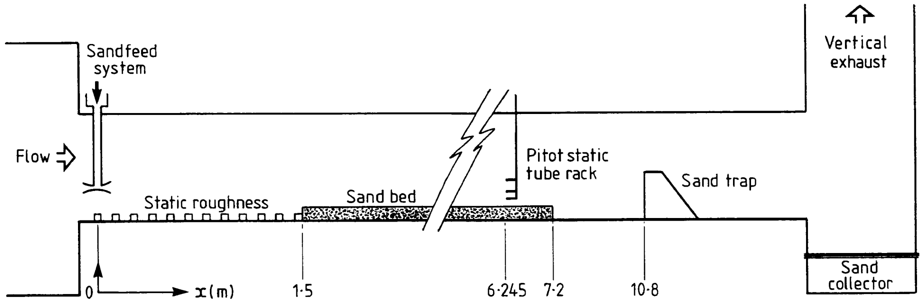

Figure 1. Schematic side elevation of the wind tunnel. The sand feed is at the co-ordinate origin from which x is measured. Static roughness is used to ensure an early rough condition extending from $x=0$ to $x=1{\cdot}5$ m. The mobile sand bed has an average grain diameter of approximately 275 µm extending from $x=1{\cdot}5$ to $x=7{\cdot}2$ m. The sand trap is located at $x=10{\cdot}8$ m. The vertical pitot static tube rack is used to determine the shear velocity of $x=6{\cdot}245$ m

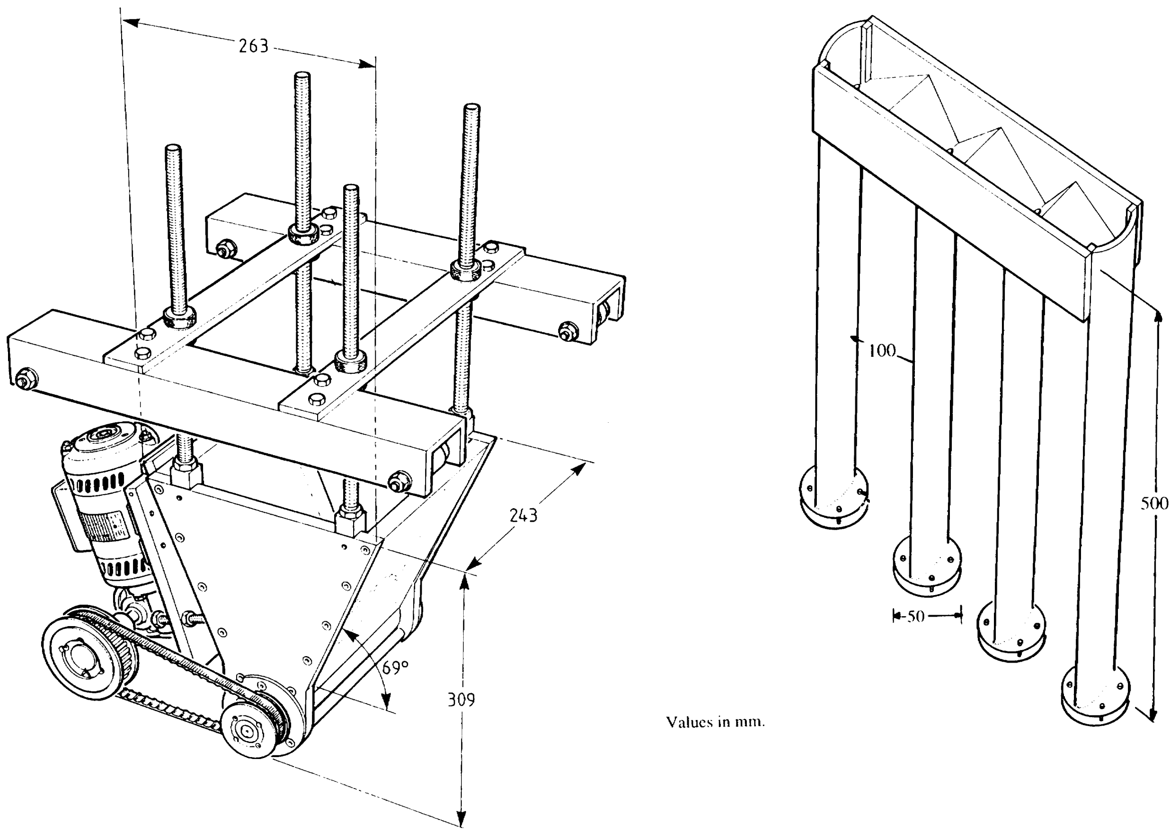

Figure 2. Schematic view of the sand feeding system. The system was installed 41 cm downwind of the tunnel's entry (Figure 1). The rate of sand feed is controlled by a variable speed motor that controls the rate of rotation of the drum, and by the number and size of grooves cut in the surface of the rotating drum. The four inlet tubes are aerodynamically shaped (each having a minor axis of 5 mm and a major axis of 22 mm), and they are distributed at equal distances across the width of the wind tunnel

bed. Due to this lag distance, the recorded values at the sand trap are calculated to incorporate about 1s delay with reference to the velocity measurement site. The sand trap, which is shown in Figure 4, is described by Al-Sudairawi (1992). The static pressure inside the trap is controlled by sliding doors on slots ventilating outside the wind tunnel so as to match the static pressure in the mouth of the trap to local static pressure in the wind

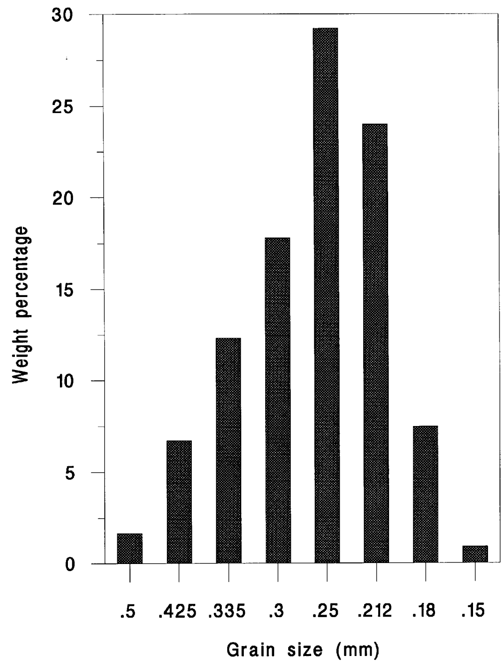

Figure 3. Size distribution of the sand used in the experiments

tunnel. The transport rate was calculated from the gradient of a graph of collected weight versus time, the gradient at each determination being averaged over 15 s.

As a first step in establishing a suitable sand feed rate at each shear velocity, three preliminary experiments were carried out without feeding. In these experiments, measurements of the equilibrium sand flux were made. The sand feed rate in later experiments was selected on evidence from these experiments. The appropriate sand feed rate was determined to be approximately 20 times the average rate of sand transport in the experiment run at the lowest shear, and approximately double to average rate of sand transport measured within the same period of run at the two higher shear velocities. The reasons for this overfeeding are two-fold. First, the sand trap's efficiency is probably between 70 and 80 per cent (Rasmussen and Mikkelsen, 1988), implying that it catches roughly 25 per cent less sand than it should. The average total catch of a similar but unventilated vertical sand trap developed by Horikawa and Shen (1960) was shown to be 0·63 per cent as efficient as an isokinetic trap (Cermak *et al*. 1982). Secondly, some sand particles are caught between the cylinders of the static roughness patch and partially fill the space between them. Thus, to quickly achieve an equilibrium population near the upstream edge of the free sand bed it was desirable to feed at more than the equilibrium transport rate. Accordingly, the chosen rates of feed were 0·12, 0·81 and 1·5 (g cm^{-1} s^{-1}) at preselected shear velocities of 22·95 (≅threshold), 37·85 and 47·75 cm s^{-1}, respectively.

Otherwise identical experiments were conducted with sand fed at three different heights, and with no sand fed. These experiments were run for short periods of time (15–30 min) depending on the preselected wind speed. Figure 5 shows the changes in the sand transport rate with time during these experiments.

VISUAL AND QUANTITATIVE OBSERVATIONS

In experiments without sand feed, the bed texture gradually started to change shortly after the start of experiments. This was more obvious in experiments with shear velocities of 37·85 and 47·75 cm s^{-1} than in the one with a shear velocity near threshold. Coarser-grained material collected at the surface and relief (ripples) started to form. The ripples formed uniform patterns and became more sharp-crested towards the end of each experiment. Similar observations were reported by Rasmussen and Mikkelsen (1991).

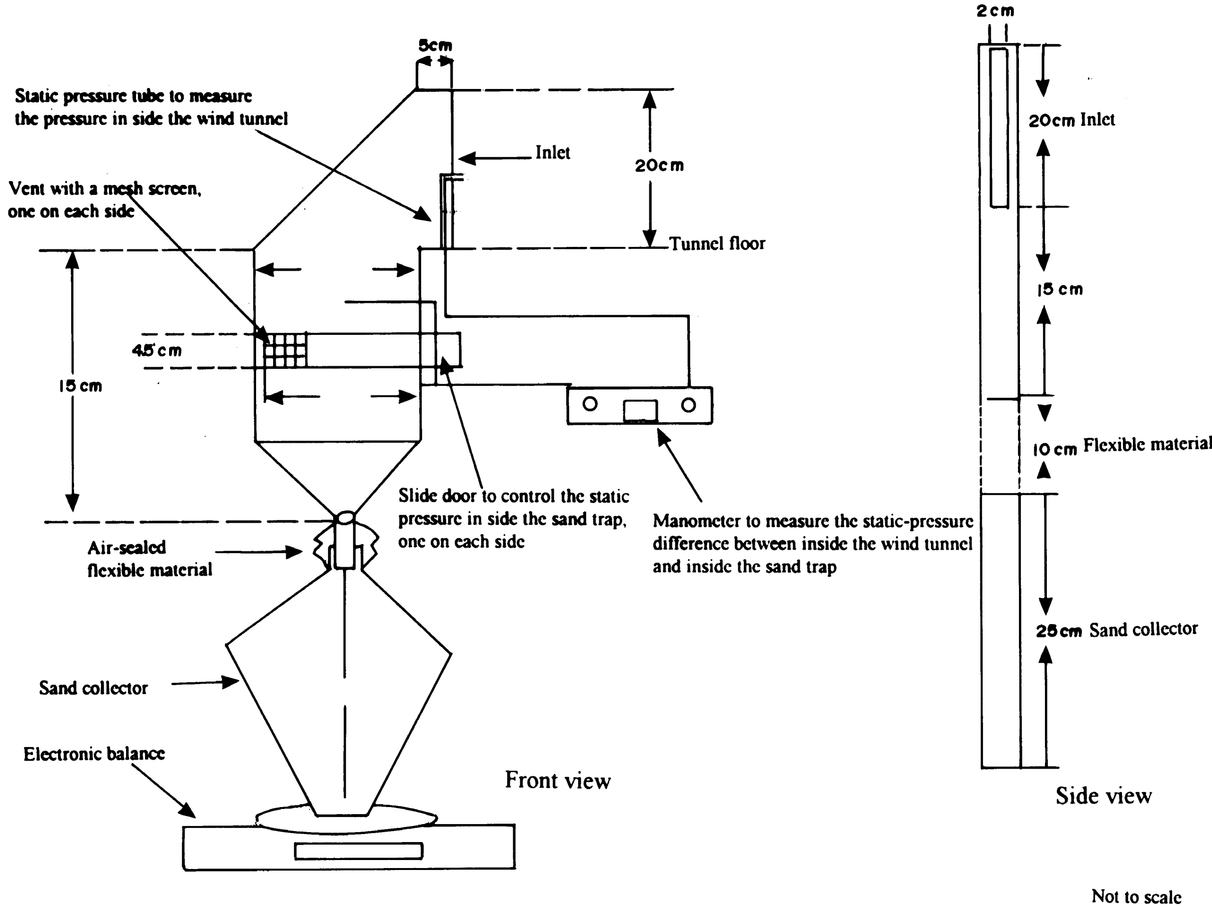

Figure 4. Schematic diagram of the sand trap (after Al-Sudairawi, 1992)

The other interesting observation was that the erosion of the sand bed began at the downwind edge at a shear velocity of 37–85 cm s^{-1}, while it began at the upwind edge of the bed at a shear velocity of 47·75 cm s^{-1}. This suggests that a greater distance is required at the lower shear velocity than at the higher one to develop steady-state saltation, which in turn affects the adjustment of the boundary layer to uniform roughness. Since the initial vertical velocity of the particle is on the order of the shear velocity of the flow (Owen, 1964), the onset of erosion at different parts of the sand bed at the two shear velocities might therefore be attributed to a mismatch between the static roughness of the fixed array and the dynamic saltation roughness. If the fixed roughness is the greater, the upstream end of the sand bed will be protected by a drop in surface shear stress at the beginning of the sand bed, and vice versa if the fixed roughness is the smaller. This observation may be better explained in terms of dislodgement capability. At 37·85 cm s^{-1}, the direct pickup capability is low, and erosion develops as the saltation population grows. At 47·75 cm s^{-1}, direct dislodgement attacks the bed immediately, creating an intense transport rate gradient at the leading edge, while saltation development produces smaller transport rate gradients downwind of the leading edge.

In the sand-fed experiments, the changes in the surface texture of the bed and the ripple formation were not so marked. A relatively smooth sand bed was observed at the end of each experiment. Sand accumulated a little downstream from the point of feeding as a deposit on the floor containing the cylinders. The dimensions of such deposits and the bed thickness changes in each experiment are given in Table I.

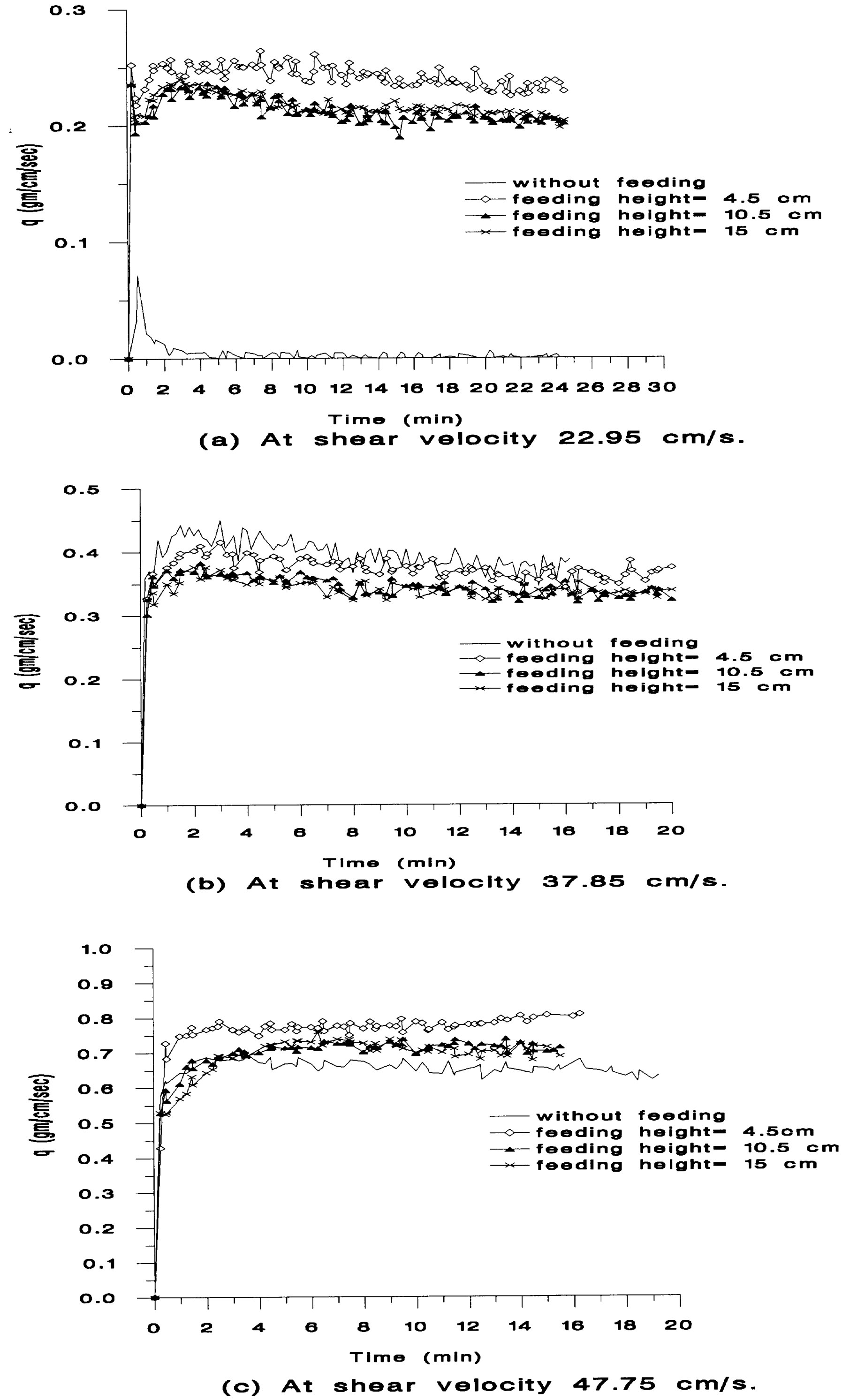

Figure 5. Sand transport rate measurements at three different shear velocities in non-fed and fed experiments

Table I. Details of deposit formation and sand bed layer thickness change due to feeding. Measurements were taken at the end of a run of the duration indicated in column 3

Case	Initial shear velocity (cm s^{-1}s)	Duration of run (min)	Rate of feed (g min^{-1})	Height of feed (cm)	Deposit height (cm)	Downstream distance of deposited sand from point of feeding (cm)	Depth of the sand bed at x = 200 cm	Depth of the sand bed at x = 400 cm	Depth of the sand bed at x = 620 cm
1	22·95	30	360·0						
1·1				4·5	1·5	10	1·5	2	2·0
1·2				10·5	–	25	1·5	1·8	1·6
1·3				15·0	1·3	41	1·7	2·0	
2	37·85	20	2453·5						
2·1				4·5	7·5	8	NA*	NA*	NA*
2·2				10·5	4·5	29	3·0	NA	1·7
2·3				15·0	3·5	60	3·0	NA	1·9
3	47·74	16	4554·5						
3·1		+1		4·5	6·5	12	2·5	2·5	1·5
3·2				10·5	2·5	123	2·5	2·2	1·5
3·3				15·0	4·5	150	4†	3·2	1·5

x indicates the distance from the position of the sand feed tubes (Figure 1).
* The depth of the bed was almost unchanged (visual observation).
† Depth of the sand bed at x = 100 cm.

DISCUSSION

Time and distance are necessary for modification of the wind structure found near the upstream edge of the sand bed to a state compatible with equilibrium sand flux. As the wind arrives at the leading edge of the sand bed, the particles have to gain momentum on the surface and then saltate. Thereafter, the effective roughness of the sand bed responds quickly to the developed saltation layer, causing an increase in the shear velocity (Owen, 1964).

According to the findings of Shao and Raupach (1992), the length of the sand bed provided in this study might be insufficient to develop equilibrium saltation and equilibrium sand flux. However, the presence of the roughness array upstream of the sand has a crucial effect on enhancement of the boundary layer development and, therefore, in sustaining equilibrium sand flux at the downwind end of the sand bed. Results of vertical velocity profiles measured along the smooth floor of the wind tunnel in clear air showed that a practical equilibrium in the shear velocity is reached in approximately 6 m, beyond which the shear velocity stays quite uniform (Abdullah, 1996). The equilibrium between the shear stress measurements and the trap transport measurements, which reflects the net change due to the combined effect of erosion and deposition at all places along the sand bed, may be assumed to exist where there is no change in the bed's elevation between the position of the pitot static tube rack and the downwind end of the sand bed. The small variation in the thickness of sand bed at or near the downwind end due to erosion and deposition processes after each experimental run (Table I), however, indicates a small degree of inconstancy in the sand-laden condition of the boundary layer.

Anderson and Haff (1988, 1991) and McEwan and Willetts (1991, 1993) have shown, numerically, that there is a time lag associated with the development of the saltating grain populations following the initial grain disturbance by lift and drag forces and then by an increasing rate of dislodging collisions. They found that this lag is 1 s, and they related it to the average hop time of the typical saltation trajectory duration, 0·2–0·3 s. This response time was in accordance with that determined experimentally by Gillette and Stockton (1989). Butterfield (1991) also provided supporting evidence for this result from wind tunnel experiments in which measurements of near-bed velocity profiles and short-period grain transport rates were made at 1 s intervals. In our measurements, the interval for calculating sand flux, whether sand feed was provided or not, was chosen to be 15 s, and therefore it was difficult to determine correctly the time lag associated with the response of the sand transport rate. However, such response was observed to be much less than 15 s. Also, for the cases run, it appeared that the lag time is a weak function of the shear velocity. A similar result was obtained from the model of Anderson and Haff (1991).

In start-up sand flux measurements (Figure 5), there is a clear peak in the maximum transport rate in most

cases, which is then followed by a diminution to reach stability. In the experiments reported here, the time at which this peak occurs seems to be a function of shear velocity, and the peak occurs over time scales of 0·5 to 1·5 min in unfed experiments and 2 to 3 min in sand-fed experiments. The point of maximum sand flux is more marked in the case of no feeding than in the case of feeding. For example, in experiments with fed sand at the rather high shear velocity of 47·75 cm s^{-1}, a peak of sand transport rate is not recognizable and maximum sand flux is reached monotonically at times of between 3 and 6 min depending on the height of feeding. The transport rate peak in unfed experiments is attributable to the discrepant rates at which the mobile grain population builds up and then extracts momentum from the wind. At peak transport rate, the grains are saltating in a boundary layer not yet fully modified by their presence. As that modification takes place, the transport rate decays from the peak value towards a lower equilibrium.

When sand is fed at the upwind end of the wind tunnel, the boundary layer is sand-laden to a degree which approximates to the natural load from the outset of the experiments. Therefore, saltation never takes place in a clear air (unnaturally energetic) boundary layer, and the overshoot in the transport rate, seen in unfed experiments, is absent unless the feed rate is badly judged. Such minor adjustments as are necessary to reduce artificial features in the saltation layer caused by inappropriate feed rates or the height of feed take place in a time scale roughly equivalent to that of the attainment of equilibrium in unfed experiments. However, during this interval, the conditions in the saltation layer are much closer to the eventual equilibrium state.

It is observed that sand transport decays more rapidly towards an equilibrium state, after reaching its maximum, in experiments without sand feed than in those with sand feed. The time to reach such an equilibrium is on the order of 2–4 min when the sand feed is turned off, and it is on the order of 8–9 min when the sand feed is turned on. The reason for this may be attributed to the fact that in the no-feed case, the saltating activity overshoots before the boundary layer profile adjusts to meet the energy requirement of grain transport. This overshooting in grain activity produces a flow resistance that is considerably higher than the steady-state resistance, and the exaggerated flow resistance increases the rate at which the flow adjustment takes place.

Generally speaking, the development of sand transport measured experimentally in this study is similar to that estimated numerically by McEwan and Willetts (1993) and Anderson and Haff (1991). However, their models differ in detail from those presented here. They found that in 1 or 2 s, the mass flux reached a maximum and then declined slightly to a stable level in less than 1 min. Butterfield (1993) found that for a sand transport rate in his wind tunnel to reach such a level of stability, a period of 100 s or so was needed. It can be seen, therefore, that these earlier studies suggest shorter time scales for sand to reach an equilibrium transport rate than were found in the present study. The experiments reported here show a longer time (several minutes) to equilibrium.

The studies using numerical models were based on periodic boundaries, i.e. simulated, closed-circle sand beds, and therefore the downwind distance was ignored in simulating the development of equilibrium sand flux. The discrepancy in time scale between the reported results and the results of numerical studies may, therefore, be attributed to the possibility that the sand transport rates measured by the sand trap (which is located 9·3 m downwind of the upstream edge of the sand bed) may lag behind transport rates over the upwind reach of the sand bed. The distinction between the model's procedures and the experimental ones lies in the fact that the models provide collision dislodgement everywhere so that flux grows synchronously. In the wind tunnel, the leading edge receives no collision to assist flux growth. Thus, transport rate peak and the attainment of equilibrium in the wind tunnel may propagate as a 'wave' downwind following the rapid development of grain activity at the leading edge of the sand bed. The observed decay in reaching equilibrium flux may also be partially attributable to the effects of the multiple grain size composition of the sand bed; the numerical models assumed a single grain size composition of the bed.

There is no doubt that grain size and shape influence transport rate (Willetts and Rice, 1988), and therefore surface resorting might also be expected to affect transport rate. The experiments confirm that size sorting of particles on the bed surface was accompanied by a significant difference in transport rate. The difference can be detected by comparing any two similar experiments of which one is fed and the other is not. In cases with fed sand, delays on the order of 1 min and on the order of 5 min were recorded in reaching maximum sand transport rates and in achieving equilibrium sand transport rates, respectively. In sand-fed experiments, the change in the surface texture of the bed was not as pronounced as it was in unfed experiments. In unfed experiments, surface

changes of texture and relief were more pronounced and equilibrium transport rate was attained more quickly. It seems probable that the surface resorting and rippling contributes to the quick establishment of equilibrium flux. Further experiments are needed to confirm this conclusion.

The trend in the sand flux measured in the wind tunnel involved four process time scales. The initial response of sand activity to imposed wind is known to be very fast, on the order of 1 to 2 s (e.g. Gillette and Stockton, 1989; Butterfield, 1991). The response of wind to sand transport load is known to be slower due to the distance and time lags caused by particle inertia. Both of these processes might be expected to be faster in sand-fed experiments than in unfed ones. The third time scale involves the propagation of transport rate changes from the upwind reach of the sand bed to the trap 9 m downwind of it. The fourth is associated with the rate of change of surface sorting and relief.

There is no inherent reason why the propagation of sand transport rate change between the sand bed and the trap should occur at different rates in experiments with fed sand and without. On the other hand, we know that the surface changes occur more slowly when sand is fed, probably because the artificial introduction of sand from all fractions smudges the development of a characteristic surface sorting. This difference is reflected in the different times taken to achieve equilibrium flux in the two cases. Thus, a significant role in the ultimate stablilzation of the transport rate can be attributed with some confidence to the changes in the population and relief which occur at the sand's surface.

CONCLUSIONS

(1) The initial response of the sand transport rate to the blowing wind in the wind tunnel is observed to be very fast, on the order of 1 s as confirmed experimentally by Gillette and Stockton (1989) and Butterfield (1991), and theoretically by Anderson and Haff (1991) and McEwan and Willetts (1991). It is also a weak function of the strength of the blowing wind.

(2) The peak of sand flux, which is a function of the strength of the blowing wind, occurs over time scales of 0·5–1·5 min and 2–3 min in unfed and sand-fed experiments, respectively.

(3) The sand transport rate usually adjust after reaching its maximum to a presumed equilibrium. The time to reach such an equilibrium was observed to be on the order of 2–4 min and 8–9 min in unfed and sand-fed experiments, respectively.

(4) The experiments suggest that the surface composition of the sand bed may have a significant effect on the development of equilibrium transport rate.

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